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Testing method for determining water resistance of wood pellets

Yoshitaka Kubojima · Takahiro Yoshida

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Abstract This study aimed at developing a simple, quantitative index for measuring the water resistance of wood pellets. Pellets made from various wood raw materials and other plant-based raw materials, as well as torrefied pellets, were used. Two aluminum plates with a size of 50 mm × 60 mm × 10 mm (about 76.6 g) with two dents were prepared. Two samples were laid on the plate in water and were covered with another plate. A displacement meter contacted the plate, and the rise of the plate because of sample swelling was recorded at 10-s intervals until the rise became stable. The effect of the weight of the aluminum plate and displacement meter were not significant. The temporal change in the diameter swelling of pellets was believed to be expressed by the equation developed. The suitable length of samples required for this test was obtained.

1 Introduction

Wood pellets, a solid fuel that is cylindrical (6–8 mm diameter, 10–30 mm length) in shape and is made from wood powder by compression, has been commercialized globally; as compared to wood chips, they have advantages such as higher energy density, better handling, higher calorific value (lower moisture), automation and miniaturization of combustion equipments and improved transport efficiency because of reduced volume. However, as compared to fossil fuels, wood pellets also have disadvantages such as a lower energy density, high cost of pellets, combustion equipment and low hydrophobic properties. Because of their low hydrophobicity, when wood pellets are impregnated with water, they swell up, lose their shape and form powder within a short time (Yoshida et al. 2011). In particular, in regions with heavy snowfall, condensation occurs on the inner walls of a silo used for storing pellets, thereby causing swelling and loss of the shape of the pellets. This swelling and shape loss are sometimes a cause of trouble in supplying fuel to a combustion equipment (Yoshida et al. 2012).

For testing their water resistance, pellets are placed in water, and the change in their shape is observed (Kuroda et al. 2009). However, the water resistance cannot be quantitatively tested by this method. Thus, this study aimed at developing a simple, quantitative index for measuring the water resistance of wood pellets.

2 Materials and methods

2.1 Materials

The pellets used for the tests are shown in Table 1. Japanese cedar (*Chryptomeria japonica* D. Don), Japanese larch (*Larix leptolepis* Gord.), konara oak (*Quercus serrata* Murray), ring-cup oak (*Quercus glauca* Thunb.), Japanese zelkova (*Zelkova serrate* Makino), poplar (*Populus* spp.) and jatropha (*Jatropha curcas* L.) were used as raw materials. Other plant-based raw materials such as oil palm (*Elaeis guineensis* Cortés), mosochiku (*Phyllostachys pubescens* Masel) and rice husk (*Oryza sativa*) were also used. In addition, several kinds of commercially available pellets were used as specimens. Their raw materials were

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Y. Kubojima (✉) · T. Yoshida
Forestry and Forest Products Research Institute, Tsukuba, Japan
e-mail: kubojima@ffpri.affrc.go.jp

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Japanese softwoods such as Japanese cedar, Japanese larch, Japanese red pine (*Pinus densiflora* Zieb. et Zucc.), pine (*Pinus spp.*). Several torrefied pellets (Kubojima et al. 2011) were also used. Pellets 1–14, 19, 20, 22, and 23 were made at the Forestry and Forest Products Research Institute (FFPRI), while others are commercially available. The diameter, length, and weight of the pellets were measured to calculate the density. The diameter and length were measured using a micrometer.

Table 1 Pellets used for the test

Pellet	Raw material	Type
1	Japanese cedar, xylem	Normal, made at Forestry and Forest Products Research Institute (FFPRI)
2	Japanese cedar, xylem	Normal, made at FFPRI
3	Japanese cedar, xylem	Normal, made at FFPRI
4	Japanese cedar, xylem	Normal, made at FFPRI
5	Japanese cedar, bark	Normal, made at FFPRI
6	Japanese larch, bark	Normal, made at FFPRI
7	Loblolly pine, xylem and bark (mixed)	Normal, made at FFPRI
8	Konara oak, xylem	Normal, made at FFPRI
9	Ring-cup oak, xylem and bark (mixed)	Normal, made at FFPRI
10	Jatropha, residue of expressed seeds	Normal, made at FFPRI
11	Oil palm, xylem	Normal, made at FFPRI
12	Oil palm, fiber	Normal, made at FFPRI
13	Mosochiku, xylem and bark (mixed)	Normal, made at FFPRI
14	Rice husk	Normal, made at FFPRI
15	Japanese cedar and pine	Normal, commercially available
16	Japanese cedar and softwoods, xylem and bark (mixed)	Normal, commercially available
17	Japanese larch and Japanese red pine, xylem and bark (mixed)	Normal, commercially available
18	Softwoods, xylem	Normal, commercially available
19	Japanese cedar, xylem	Torrefied pellet made from chips treated in a rotary kiln at 215 °C, made at FFPRI
20	Japanese cedar, xylem	Torrefied pellet made from chips treated in a super-heated steam reactor at 240 °C, made at FFPRI
21	Poplar, xylem	Torrefied pellet made from chips treated at a moving-bed reactor at 250 °C, trial sample
22	Japanese cedar, xylem	Torrefied pellet made from pre-pelletized material, subsequently treated at 240 °C in a vacuum oven, made at FFPRI
23	Japanese cedar, xylem	Torrefied pellet made from pre-pelletized material, subsequently treated at 250 °C in a vacuum oven, made at FFPRI

To investigate the effect of pellet length on the water resistance, 10–30-mm-long pellets were used for pellets 2, 8, 9, and 13. According to the "Quality standard of wood pellet" (Japan Wood Pellet Association 2011), pellets with a length less than 30 mm do not clog the combustion equipment.

Pellets were conditioned at 20 °C and 65 % relative humidity. All tests were conducted under the same conditions.

2.2 Testing system for swelling of pellets

A testing and calculating system for the water resistance of pellets (TW-36, Takachihoseiki Co., Ltd., Tokyo, Japan) was developed. Two aluminum plates of dimensions 50 mm × 60 mm × 10 mm (about 76.6 g) with two dents were prepared. Two samples were laid on the lower plate and covered with the upper plate. As shown in Fig. 1, a displacement meter contacted the upper plate, and the rise of the upper plate because of sample swelling was recorded at 10-s intervals until the rise became stable (Pellets 22 and 23: 24 h, Others: 4 h). The samples were laid on the lower plate without water for about 10 min at the initial stage to examine the effect of the weight of the aluminum plate and the displacement meter. After about 10 min (=t_0), water was poured into a container.

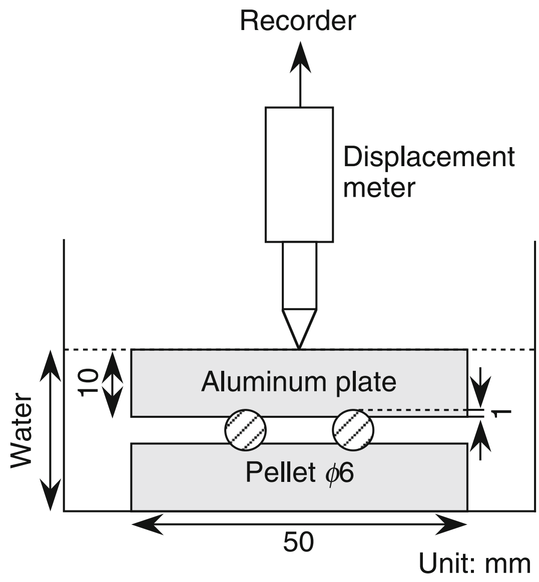

Fig. 1 Apparatus for determining water resistance of pellets

The "diameter swelling DS [%]" was defined as the ratio of the rise of the upper plate to the initial diameter of the samples. The temporal change in the diameter swelling was approximated by the following equation based on the approximation for the temporal change in the thickness swelling of wood-based boards (Suzuki et al. 1985; Suzuki and Saito 1988; Suzuki and Miyamoto 1998; Sekino et al. 2000):

$$DS = a_1\left\{1 - exp\left(-\frac{t - t_0}{b_1}\right)\right\} + a_2\left\{1 - exp\left(-\frac{t - t_0}{b_2}\right)\right\} \quad (1)$$

where t is time and a_1, a_2, b_1, and b_2 are empirical constants. The constant a represents an estimated saturation value when t tends to infinity, and the constant b indicates a rate of increase (Suzuki and Miyamoto 1998). The equation for the thickness swelling of wood-based boards has only the term containing a_1 and b_1. Since this equation did not fit measurements well, the term containing a_0 and b_2 was added.

The initial differential coefficient of Eq. (1) at $t = t_0$ $a_1/b_1 + a_2/b_2 = IDC$ was examined to determine whether or not it was useful as an index of the water resistance of pellets. The high and low values of the initial differential coefficient imply the low and high water resistance, respectively.

3 Results and discussion

Figure 2 shows an example of the pellet shape after the test (Pellet 2), and Fig. 3 shows an example of temporal changes of the pellet diameter swelling (Pellet 1). A cylindrical shape was maintained and the diameter swelling was constant in the range $0 \leq t \leq t_0$. This suggests that the effect of the weight of the aluminum plate and the displacement meter was not significant in this time region.

The measured data and the approximated results calculated using Eq. (1) are in agreement, as shown in Fig. 3. The correlation coefficients of approximation were very high, more than 0.99 for almost all the pellets with a wide range of the initial differential coefficients (0.0031–17.2 %/min), as shown in Table 2. Hence, it is believed that the temporal change in the diameter swelling of pellets can be expressed by Eq. (1). One of the reasons why Eq. (1) was useful in estimating the temporal changes in the diameter swelling of pellets is that both the wood-based boards and pellets are made by compressive elements, although an adhesive is used for the wood-based boards and not for the pellets.

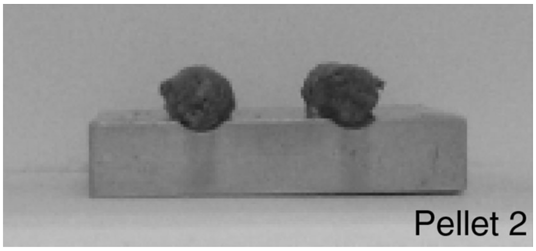

Fig. 2 Example of the pellet shape after the test (Pellet 2)

Water enters into a pellet from both its side and the end. The ratio of the end area to the side area of a pellet increases with a decrease in the length. From this point of view, it was expected that there is a significant relationship between the initial differential coefficient and the length, but such a relationship was not obtained for all four kinds of pellets, as shown in Fig. 4. The regression equations were

$$IDC = 0.0086L + 6.8\,(r = 0.5421,\ \text{NS})\ \text{for Pellet 2} \quad (2)$$

$$IDC = -0.26L + 25.5\,(r = 0.6231,\ \text{NS})\ \text{for Pellet 8} \quad (3)$$

$$IDC = 0.0040L + 1.8\,(r = 0.5274,\ \text{NS})\ \text{for Pellet 9} \quad (4)$$

$$IDC = -0.022L + 7.7\,(r = 0.2808,\ \text{NS})\ \text{for Pellet 13} \quad (5)$$

where L and r are the length and the correlation coefficient, respectively. NS means "not significant". This may be because the influence of the ratio was smaller than the variance in properties of pellets themselves.

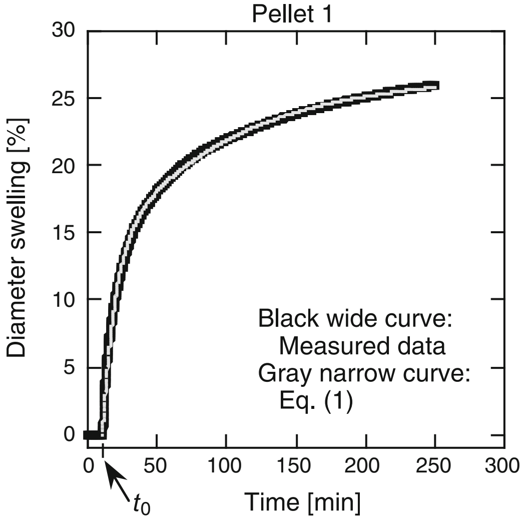

Fig. 3 Example of temporal changes of the diameter swelling (Pellet 1)

Table 2 Diameter, length, density, and initial differential coefficient of pellets and correlation coefficient calculated by approximation using Eq. (1)

Pellet	Diameter (mm)	Length (mm)	Density (kg/m^3)	Initial differential coefficient (%/min)	Correlation coefficient
8	6.2	21.9	1,306	17.2	0.9895
15	6.3	21.4	1,270	16.5	0.9952
17	6.1	23.5	1,167	14.2	0.9772
2	6.2	20.3	1,332	8.3	0.9941
13	6.2	21.6	1,257	7.4	0.9977
16	6.1	20.7	1,229	5.4	0.9988
18	6.4	21.4	1,243	5.0	0.9988
11	6.2	20.1	1,299	4.8	0.9985
19	6.2	22.8	1,329	4.5	0.9958
7	6.2	19.7	1,242	4.1	0.9995
9	6.2	19.6	1,320	3.4	0.9987
4	6.1	21.4	1,272	2.2	0.9983
3	6.1	19.7	1,197	2.1	0.9990
21	6.1	20.5	1,234	1.9	0.9990
1	6.2	20.8	1,310	1.6	0.9995
20	6.0	20.6	1,314	1.5	0.9970
14	6.2	19.1	1,320	1.1	0.9996
12	6.2	14.3	1,005	0.42	0.9983
10	6.3	19.1	1,146	0.069	0.9996
5	6.2	21.2	1,373	0.031	0.9996
6	6.1	17.8	1,272	0.019	0.9998
22	5.9	16.8	1,123	0.0049	0.9998
23	5.8	17.8	1,086	0.0031	0.9986

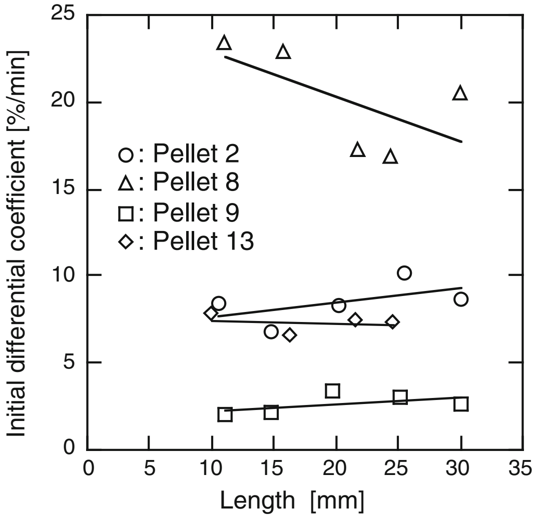

Fig. 4 Relationship between the initial differential coefficient and length of pellets

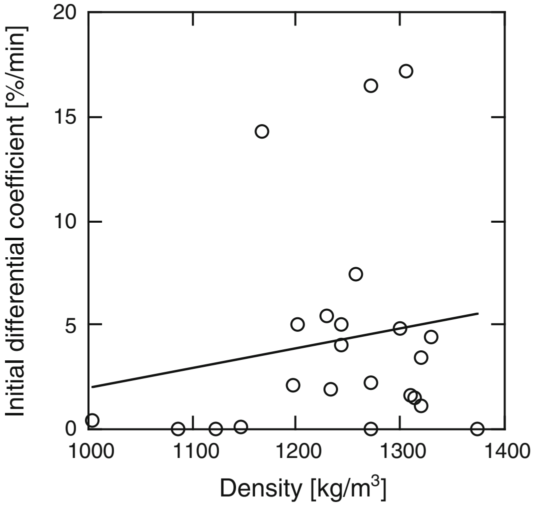

Fig. 5 Relationship between the initial differential coefficient and density of pellets

Table 3 Averages and coefficient of variance of correlation coefficient and initial differential coefficient calculated by approximation using Eq. (1) for various time regions

Pellet	Correlation coefficient		Initial differential coefficient (%/min)	
	Average	Coefficient of variance	Average	Coefficient of variance
8	0.9957	0.3	20.4	7.6
15	0.9939	0.3	17.8	4.5
17	0.9834	0.6	12.3	15.5
2	0.9977	0.2	8.2	3.0
13	0.9978	0.1	8.0	4.1
16	0.9971	0.6	6.2	6.9
18	0.9994	0.0	5.7	7.0
11	0.9981	0.3	5.4	5.7
19	0.9795	2.3	4.3	9.6
7	0.9989	0.2	4.4	3.9
9	0.9982	0.3	3.9	6.0
4	0.9862	1.8	2.2	6.3
3	0.9951	0.5	2.2	6.0
21	0.9935	0.6	1.8	6.4
1	0.9969	0.4	1.7	5.8
20	0.9844	1.6	1.4	5.6
14	0.9950	0.9	1.2	9.6
12	0.9892	1.3	0.38	14.1
10	0.9881	1.8	0.081	9.7
5	0.9961	0.6	0.044	16.9
6	0.9952	0.5	0.044	12.6
22	0.9993	0.1	0.0052	3.3
23	0.9977	0.2	0.0078	61.0

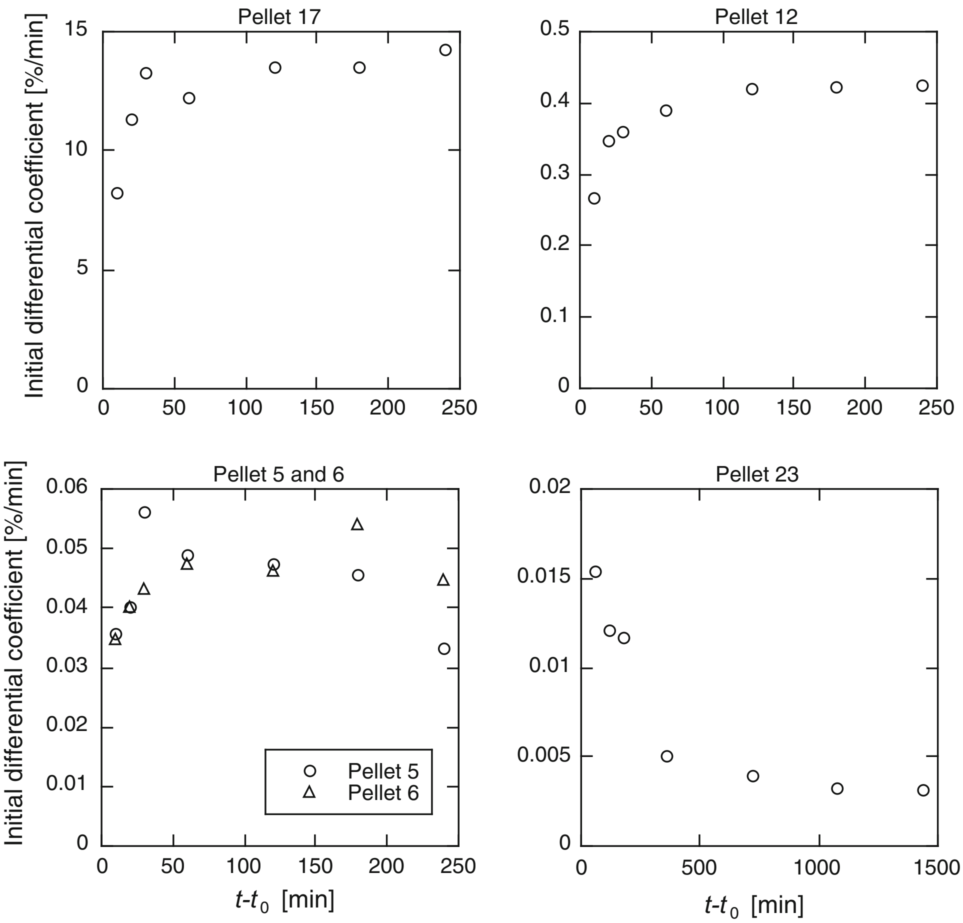

Fig. 6 Relationship between the initial differential coefficient of pellets and time region of approximation using Eq. (1)

When the samples were too short (10 mm), it was sometimes difficult to keep the upper plate parallel to the lower plate because placing samples exactly in the middle in the longitudinal direction of the plate (60 mm) was difficult. When the samples were too long (25 and 30 mm), some samples were slightly curved before the test. Hence, 15–20-mm-long samples were believed to be suitable for the plates used in this study. The suitable length will be subject to the length of the plate.

Some kinds of pelletes had a low initial differential coefficient. The low values for pellets made from bark (Pellet 5 and 6) were similar to the previously obtained results (Kuroda et al. 2009). The torrefied pellets may be hydrophobic because of the tar created by torrefaction. In addition to the hydrophobicity of the elements themselves mentioned above, torrefaction also breaks down the carbohydrates, whereupon the ability to establish hydrogen bonds between the polymer chains of adjacent elements can be assumed to decline significantly (Stelte et al. 2011). Hence, the initial differential coefficient may reflect the bonding strength between the elements such as the mechanical durability (Sawabe et al. 2005). If the initial differential coefficient reflects the bonding strength between the particles, it is expected that there will be no relation between the initial differential coefficient and density, pellets with low density do not always tend to have a high initial differential coefficient, swell up and change their shape into powder within the short time. As expected, there was no significant relationship between the initial differential coefficient and density (Fig. 5) according to the following Eq. (6):

$$IDC = 0.0096\rho - 7.6\,(r = 0.1659,\ \mathrm{NS}) \tag{6}$$

where ρ is the density.

As mentioned above, the temporal change in the diameter swelling can be expressed by Eq. (1) with a very high correlation. Such a high correlation will be maintained even if the approximation region reduces. In other words, the water resistance of pellets can be tested in a shorter time. Thus, the approximation given by Eq. (1) was performed for various time regions: $0 \leq t\text{–}t_0 \leq 60$, 120, 180, 360, 720, 1,080, and 1,440 min for Pellets 22 and 23, $0 \leq t\text{–}t_0 \leq 10$, 20, 30, 60, 120, 180, and 240 min for others. For various time regions, the correlation coefficient was high while the initial differential coefficient varied for several pellets (17, 12, 5, 6, and 23), as shown in Table 3.

The initial differential coefficient was plotted against the time region for approximation, as shown in Fig. 6. The initial differential coefficient tended to become stable when the time region was sufficiently long. The correlation coefficients of approximation using Eq. (1) were very high as mentioned above, but they were not exactly equal to 1. Hence, it is thought that the initial differential coefficient varied when the time region was short. This suggets that a minimum testing time exists. Based on these results, it was concluded that although it is possible to reduce the testing time the minimum testing time should be investigated in detail. It is thought that the minimum testing times for the pellets used for this study are 60 and 360 min for the normal and torrefied pellets in Fig. 6, respectively.

To standardize this testing method, several points should be investigated. For example, the number of samples to be tested needs to be optimized because the properties of pellets vary. It should be determined whether or not the average and the lower limit of the initial differential coefficient can be used. The threshold value of the initial differential coefficient that secures the practical water resistance of pellets should be determined by comparison with the results of other tests, for example, the outdoor exposure tests under conditions of actual use.

4 Conclusion

A simple testing system to measure the water resistance of pellets was developed. The results obtained were as follows:

1. Since the cylindrical shape was maintained and diameter swelling was constant over the range of $0 \le t \le t_0$, the weight of the aluminum plate and the displacement meter did not play a significant role.
2. Since the measured data and approximated results calculated using Eq. (1) were in agreement, the temporal change in the diameter swelling of pellets was believed to be expressed by Eq. (1).
3. The effect of the ratio of end area to side area of a pellet was small, and a suitable length of samples was obtained for the test.
4. Although it is possible that the testing time can be reduced, the minimum testing time that can be used should be investigated in detail.

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